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CASE POSTALE 6128, SUCCURSALE A, MONTRÉAL, QUÉBEC, H3C 3J7

A MODEL FOR THE STRATEGIC PLANNING OF NATIONAL FREIGHT TRANSPORTATION BY RAIL

by

Teodor Gabriel Crainic*
Michael Florian*
José-Eugenio Leal+

* Centre de recherche sur les transports, Université de Montréal, Montréal, CANADA.

+ Pontificia Universidade Catolica de Rio de Janeiro, Rio de Janeiro, BRAZIL.

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ABSTRACT

Recently, we developed a multimode multiproduct network optimization model that is the main model of STAN, an interactive-graphic system for the strategic analysis and planning of national freight transportation systems. For STAN, we developed a model of the rail freight transportation system, its components, operations and goals, that is compatible with both the strategic objectives of the planning system and the representation of the other transportation modes that compose a national multimode transportation system. The objective of this report is to present and analyse this strategic model of a national freight rail transportation system. We also examine how the rail model is integrated into STAN, as well as how the system may be used to model a number of realistic scenarios.

KEY WORDS: RAIL FREIGHT TRANSPORTATION,
NETWORK OPTIMIZATION MODELING,
STRATEGIC PLANNING.

RESUME

Nous avons récement mis-au-point un modèle d'optimisation de réseau multimode multiproduit qui constitue le noyau méthodologique de STAN, un système interactif-graphique pour l'analyse et la planification stratégiques des réseaux nationaux de transport de marchandises. A cette occasion, nous avons également développé un modèle d'un système national de transport ferroviaire, avec ses buts, composantes et principales opérations, compatible en même temps avec les objectifs stratégiques du système de planification et avec les modélisations des autres modes de transport. Ce rapport présente et analyse cette formulation stratégique d'un système national de transport des marchandises par rail. Il présente également, comment ce modèle s'intègre dans le modèle global de STAN et examine quelques applications.

MOTS CLES: TRANSPORT FERROVIAIRE DE MARCHANDISES,
MODELES D'OPTIMISATION DE RESEAUX,
PLANIFICATION STRATEGIQUE.

I. INTRODUCTION

Rail is an important part of any serious national freight transportation study. Consequently, a significant amount of the understanding and methodological effort necessary to build a comprehensive model of a national transportation system has to be dedicated to an adequate representation of the rail mode and its interactions with the other components of the transportation system. Several reasons explain this fact.

Rail usually transports large quantities of freight on relatively long distances and is perceived as a most energetically efficient transportation mode in these cases. Therefore, it is an important economic activity that involves infrastructure and equipment representing significantly large capitalisations and that employs, either directly or undirectly, a large work force. Modifications to rail infrastructure generally require large investments and long periods of time both for their planning and realisation.

Like other transportation modes, transport by rail is usually regulated by one or several governmental agencies. Often, rail companies are either state owned or state controled. Consequently, rail transportation is often viewed, especially in developing countries, as a privileged economic and social lever to boost national unity and integrity, to control energy costs, to open up new regions to population and economic development, to bring products for export from the producing regions to ports and to transport imported goods to the consumption centers of the country, etc. This view is equally often shared by the international agencies which usually supply the funds for projects in developing countries that require large investments.

Recently, we developed a multimode multiproduct network optimization model (Florian et al. 1986a, Crainic, Florian and Guélat 1987a,b), that is the main model of an interactive-graphic system for the strategic analysis and planning of national freight transportation systems, called STAN (Florian et al. 1986b). For STAN, we developed a modeling of the rail freight transportation system, its components, operations and goals, that is compatible with both the strategic objectives of the planning system and the representation of the other transportation modes that

compose a national multimode transportation system.

The objective of this report is to present and analyse this strategic model of a national freight rail transportation system. We also examine how the rail model is integrated into STAN, as well as how the system may be used to model a number of realistic scenarios.

First, we want to recall that the initial motivation for the development of STAN, as well as its first applications, came from a cooperative project carried out jointly by the Centre de Recherche sur les Transports of the Université de Montréal, the Pontifícia Universidade Católica do Rio de Janeiro and GEIPOT, the national transportation planning agency of the brazilian Ministry of Transportation. The project, partially financed by the International Development Research Centre, was concerned with the *Strategic Planning of Freight Transportation in Brazil*. It is thus natural that some of the features of the national strategic rail model be inspired by the brazilian transportation context. However, the brazilian transportation system is sufficiently complex to require a modeling framework that fits most other rail transportation systems.

The report is organized as follows. Section II presents a brief review of the components, organization and operations of a rail freight transportation system, as well as a brief survey of some previous rail strategic modeling efforts. Section III consists of a short description of STAN, its modeling framework and its impact on the representation of the rail mode. Section IV is dedicated to the detailed description of the rail network model and the formulation of the cost and delay functions. In Section V we briefly discuss the empty car distribution problem in the context of strategic planning. We conclude with the presentation of possible utilization modes of the rail model.

II. RAIL FREIGHT TRANSPORTATION

The physical infrastructure of any rail system consists of a complex network made up of a number of large terminals *(classification yards)*, numerous small stations and junction points interconnected by main and secondary lines. At any given moment, a large number of rail cars, either empty or loaded with a specific commodity, are in the network, and each one may have a particular objective, independent of all the others. The Canadian National Railways' network, for example, has over 5000 yards and stations and serves 22,000 operated mainline miles of track. On this network, one finds more than 100,000 CNR and foreign cars (CNR, 1983).

Cars do not move independently, however, but in formations called blocks, which in turn are grouped into convoys called *trains*. Blocks are groups of cars, with possibly different final destinations, arbitrarily considered, for all operational purposes, as a single unit from the yard where the block is assembled till its destination yard where its component cars may be reclassified and put in a new block. One or more blocks, plus the necesssary engines, make up a train.

All station to station movements in a rail network are performed by trains. Trains travel following predefined routes (and schedules, eventually) at specified frequencies over a planning period. The route, frequency and other operational characteristics, such as train type, speed, priority, etc., define the *train service*. On a medium to long term planning horizon, the train service network specifies all possible movements throughout the network and thus defines the operating cost structure of the system.

Characteristically, rail vehicles are captive to the infrastructure: cars and engines move exclusivelly on rail tracks. This captivity and the fact that in most rail systems several different types of train services (e.g. passenger, fast freight, unit, normal freight, etc.) are operated concomitantly, sometimes on single track rail lines, generate the train meetings and overtakes on the tracks of the network which are so characteristic of the rail mode. Consequently, other than the usual physical *capacities* of the links, in analysing rail transportation one has also to pay considerable attention to the *over-the-line delays* which represent, for a specific train type, the travel time over the link, given the link characteristics and the *train*

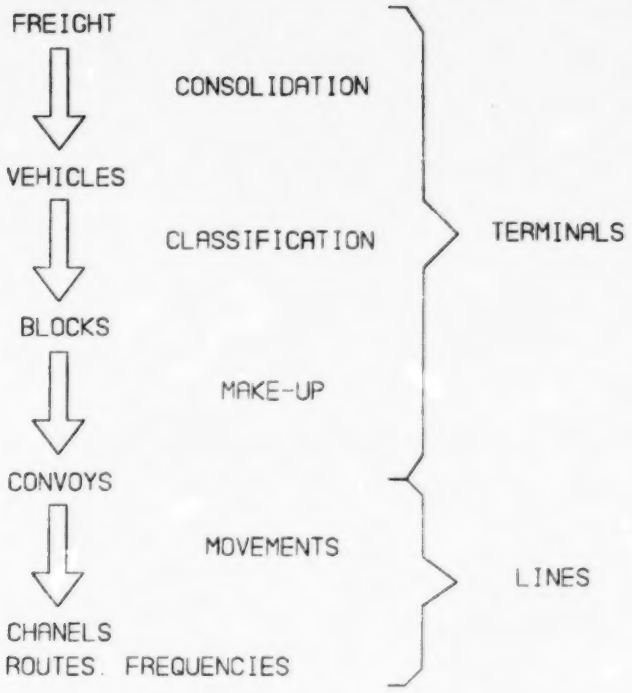


Figure 1. Rail organization

congestion, generated by the total train traffic in both directions on the link.

This organization and its successive aggregations, summarized in Figure 1, are characteristic to the rail mode and, when properly planned, generate economies of scale resulting in increased efficiency. They are also responsible, however, for more complex yard operations, more intricate cost and delay formulae and additional planning problems.

To control and plan the operations of such a generally vast and complex system, rail companies establish a number of rules and policies at all levels of decision making in the company. Thus, operational policies deal dynamically and in great detail with local operations: train time-tables, track priority rules, yard dispatching policies, engine and empty car scheduling and so on. These policies generally follow the guidelines established at the tactical level of decision-making, where general, network-wide operating strategies are generated. The resulting *transportation plan*

specifies general yard car classification and train formation policies, the design of the service network (the train services to run, their routes and frequencies) and the routing of traffic through the physical and service networks, to satisfy global economic and service criteria. Strategic decisions are concerned with the long term evolution of the company: major investments, important modifications to the physical infrastructure or to the operating policies, etc. Often the possible impact of strategic decisions is evaluated by generating and analysing the corresponding transportation plan. Assad (1980), Crainic (1986, 1987), Dejax and Crainic (1987) present model formulations (mostly from the operations research field) aimed at these problems.

The rail mode is present in most models of national/regional multimode transportation systems. It has also received quite a great deal of attention as a single mode multicarrier problem (Crainic, 1986). However, none of these modeling approaches answers our aim. The Harvard Model (Kresge and Roberts, 1971), is the first significant predictive freight network model which was conceived for the national planning of a developing country. It has only "modal" routes as links (no representation of the physical network) and congestion phenomena are not considered. The Multi-State Transportation Corridor Model (McGinnis et al., 1981, Jones and Sharp, 1979, Sharp, 1979) considers an explicit multimodal network but, costs are linear, congestion is ignored and backhauling is not considered. Congestion is also ignored in the Transportation Network Model (Bronzini, 1980). The Freight Network Equilibrium Model (Friesz, Gottfried and Morlok, 1986) does include nonlinear costs and delay functions that model congestion phenomena; but, it is a sequential model using two network representations: an aggregated skeletal user-perceived network where product flows are determined by mode and carrier, and separate networks for each carrier acting alone to minimize its costs, akin to a tactical planning perspective. The single mode formulations (Kornhauser et al., 1979, Lansdowne, 1981, Bronzini and Sherman, 1983, etc.), generally consider more detailed network and operational representations, even if backhauling is not usually considered. However, there are no simple ways of integrating them into more general multimode models.

Our goal is to achieve an aggregate, *strategic*, modeling of the transportation of freight by rail that may, on one hand, adequately reflect the economics and spatial-temporal relations typical to the rail mode. We have to acknowledge, therefore, the importance of the train movements and yard operations, especially car classification, that define a large part of the system's operating costs and generate congestion, and thus delays, in the yards and on the links of the network. On the other hand, our formulation has also to respect the conventions and general guidelines of the general model for the strategic planning of a multimode multicommodity national freight transportation system on which STAN is based.

III. STAN - A BRIEF PRESENTATION

STAN stands for Strategic Transportation ANalysis. It is an interactive graphic multiproduct multimode system for national or regional strategic planning of freight transportation. The strategic level of planning implies a medium to long term time horizon and a rather aggregate level of detail for the representation of the transportation infrastructure and provided services.

The primary role of STAN is the comparison and evaluation of alternatives. The contemplated alternatives normally represent major changes to the transportation infrastructure or important modifications to the operating policies and cost structures. They may also represent anticipated or predicted modifications to the magnitude and distribution of the demand for transportation for some or all products, between some or all origin-destination points in the region. Then, an existing situation is usually described by one of the scenarios of the data base and a simulation of the freight flows is carried out. Alternative situations are described by other scenarios of the data base. The simulation of freight flows is carried out on these scenarios as well. Subsequently, flows, link costs, delays and congestion, intermodal shipments, infrastructure utilization and other performance factors may be compared between different scenarios in order to carry out various analyses (e.g. cost/benefit).

STAN is the first interactive-graphic system specially designed for strategic planning of freight flows at the national or regional level. It allows the planner to engage in the planning process by using terminology he is familiar with and minimizes data processing and computer programming type of tasks. The system also permits the interactive-graphic manipulation of the data bank (networks, matrices, functions, etc.), as well as the instantaneous visualization of input data, results of computation and all other information retrieved from the data base, in either graphic or list form. Florian et al. (1986b) describe the main features of the system.

The network optimization model that is used to simulate network flows in STAN is a non-linear multimode multicommodity assignment formulation that minimizes the *total generalized system cost* while satisfying the usual flow

conservation constraints:

$$\textit{Minimize} \sum_{p \in P} \left[\sum_{a \in A} s_a^p(v) * v_a^p + \sum_{t \in T} s_t^p(v) * v_t^p \right]$$

Subject to

$$\sum_{k \in K_{od}^p} h_k = g_{od}^p \qquad o \in O,\ d \in D,\ p \in P$$

$$h_k \geq 0 \qquad k \in K_{od}^p,\ o \in O,\ d \in D,\ p \in P$$

where,

N : set of nodes;

L : set of links;

T : set of transfers;

O : set of nodes where demand originates;

D : set of nodes where demand terminates;

M : set of modes;

K_{od}^p : set of multimodal paths joining origin o to destination d for product p;

g_{od}^p : demand of product p to be moved from origin o to destination d;

h_k : flow on path k, $k \in K_{od}^p$;

v_a^p : flow of product p on link a

$$v_a^p = \sum_{k \in K^p} \delta_{ak} * h_k \qquad a \in A,\ p \in P;$$

δ_{ak} : 1 if link a belongs to path k ; 0 otherwise;

v_t^p : flow of product p on transfer t

$$v_t^p = \sum_{k \in K^p} \delta_{tk} * h_k \qquad t \in T,\ p \in P;$$

δ_{tk} : 1 if transfer t belongs to path k ; 0 otherwise;

K^p : set of all paths for product p;

s_a^p : generalized cost on link a for product p;

s_t^p : generalized cost on transfer t for product p.

The generalized cost is computed, for each link and transfer of the network, as the weighted sum of an operating cost function, a delay (passing throught time) function and an energy consumption function. The nonnegative weights reflect the relative importance of each cost component for a particular application, while the delay and energy consumption functions ensure the translation of time and energy units into monetary units.

According to the definition of the mode set M, this formulation represents either the entire national/regional multimode transportation system, or a part of it, a subsystem of specified transportation modes. It is thus the mathematical formulation of the national freight rail transportation system that we use.

A detailed description of the general STAN model may be found in Crainic, Florian and Guélat (1987a). Here, we only highlight some of the main features of the formulation, that are relevant for the modeling of the rail mode:

- All traffic (i.e., all flow variables) are mesured in tons only;
- There are no explicit capacity constraints on the links, nodes or transfers of the network;
- Parallel links are allowed in the network, each link being used exclusively by a specific mode;
- Transfers may be defined at a node between specific modes;
- Total generalized system cost is the sum of the individual link and transfer generalized costs;
- The global objective, i.e. the total generalized system cost, is assumed to be a convex differentiable function, as required by the solution method described in Crainic, Florian and Guélat (1987b).

This modeling framework provides both an adequate representation of large multimode multiproduct transportation systems for strategic planning purposes and a mathematical structure well suited for efficient solution methods even when large problems are solved on small computers. It also imposes limitations in the

representation of the individual transportation modes, especially rail. We have, in spite of this, achieved a model of rail freight transportation that reconciles the requirements of strategic planning with the complexity of rail operations. The details of the model related to the rail mode is the object of this report.

IV. RAIL MODELING

The requirements of a national model for the evaluation of strategic decisions imply that a number of typical rail elements may not be explicitly described on the network. In particular, path information, from origins to destinations, is not availble in the model, implying that train services and frequencies cannot appear in the formulation. Hence, approximations are used.

The network representation, on the other hand, has to be rather detailed and specific, since an important class of scenarios considered in STAN reflect modifications in the infrastructure and their impact on the utilization of the various transportation modes. The network model should therefore be able to reflect adequately the interaction between the physical characteristics of the infrastructure and the performance of the transportation system: traffic distribution and mode utilization, congestion and bottlenecks, etc.

Our modeling framework aims at satisfying these objectives. We first present the network representation, then the flow and cost functions and, last, the formulation of the delay functions.

4.1 The modeling of the rail network

The rail infrastructure is represented by a network, $G = (N, A, T)$, composed of nodes, links and transfers.

The set of *nodes* includes centroids and regular nodes. Regular nodes represent physical locations on the network: yards, stations, junctions, intermodal transfer facilities, etc. *Centroids* are dummy nodes that correspond to regional subdivisions; all the demand for transportation, that either originates from or terminates at a particular region is "concentrated" at the associated centroid. Centroids make up the sets O and D. No regular node may be the origin or the destination of any traffic.

Links represent the rail tracks that connect two points in N. Links have a number of physical characteristics, such as length, capacity, etc. We further examine the notion of link capacity in Section 4.3. Product volumes, v_a^p for $p \in P$, and the operating cost, delay and energy consumption functions necessary to compute

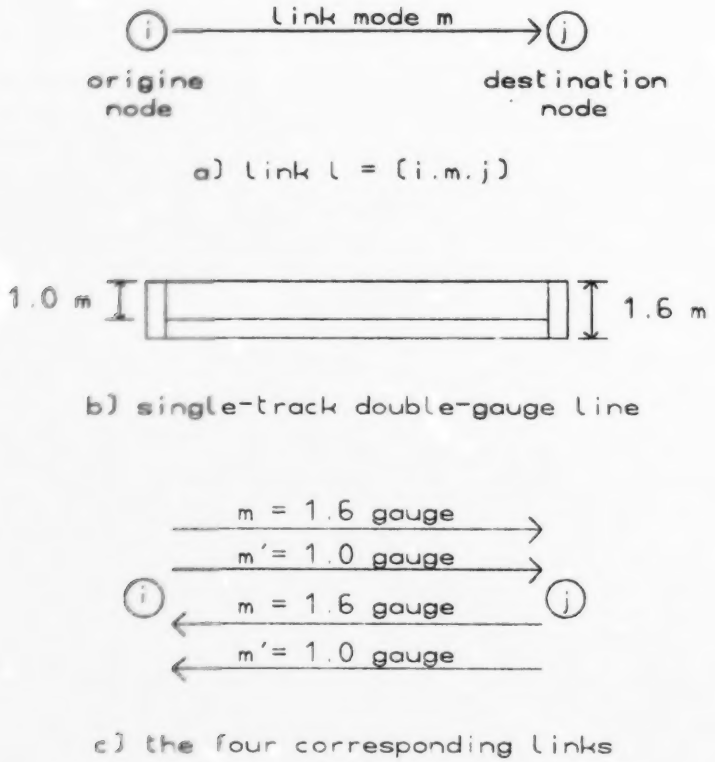


Figure 2. Rail line modelization

the generalized cost are associated with each link a.

The network is composed of directed links with one mode allowed on each link, as illustrated in Figure 2a. When more than one mode serves two adjacent nodes, parallel links may be defined between these nodes. Some, or all, of these parallel links may share the same infrastructure or capacity.

These features allow, for example, the representation of different rail companies, track gauges or, under some additional hypotheses and limitations, various classes of transportation services as different transportation modes. Figure 2 illustrates the richness provided by this modeling approach: a single track with double gauge (physically, three rails are installed and trains of both gauges travel in both directions over the line - see Figure 2b) is represented as four links: two (one for each direction of travel) links for each gauge defined as a separate mode. Note that, in this example, the four links share the same capacity.

Connectors are a particular group of links that "connect" the centroids to the rest of the network. Connectors have, therefore, all the characteristics and properties of regular links and are used to model the access to the transportation infrastructure. For instance, one may use connectors to model the situation where some specific products enter or leave a given region via some particular stations. In the example illustrated in Figure 3, products may leave the region-centroid **C** either via node **i** or node **j** and products may enter the region either via node **i** or node **k**. Node **h** is neither an initial nor a terminal node for any traffic movement. Furthermore, by adroitly adjusting the cost fuctions (e.g. infinite transportation costs on the C - j connector), one may specify that a particular group of products leave the region exclusively through, say, node **i**.

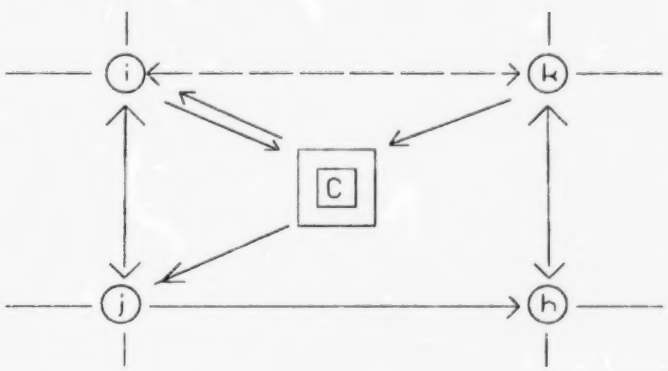
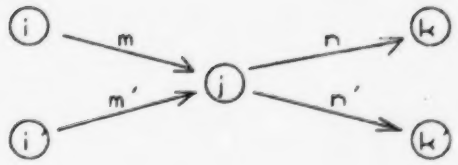
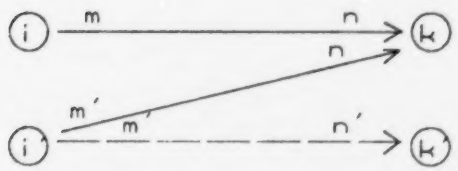


Figure 3. Connectors

Transfers represent intermodal movements at nodes, as illustrated in Figure 4. In our model, freight paths may be composed of links with different modes, only if the appropriate transfers have previously been defined at the nodes of the path. In STAN, transfers are represented by a quintuple that identifies the transfer node, the node and mode (hence, the link) where the transfer initiates, as well as the node and mode of destination of the transfer (see Figure 4a). However, it is also useful to refer to the link-like representation of transfers, as illustrated in Figure 4. Functions, of cost, delay and energy consumption, and product flows, v_l^p for $p \in P$, are associated with each transfer.



a) transfers $t_1 = (i, m, j, n, k)$
$t_2 = (i', m', j, n, k)$
$t_3 = (i', m', j, n', k')$



b) transfer representation as links
$t_1 = (i, m - n, k)$
$t_2 = (i', m' - n, k)$
$t_3 = (i', m' - n', k')$

Figure 4. Transfers

Transfers may evidently be used to model intermodal transfer facilities between rail and other transportation modes. For the rail mode, transfers may also be used to represent the junction points between the networks of two different rail companies and the transfer operations performed therein, or the transshipment points from one gauge to another in a rail company's network. Transfers could be used to model classification yards but the resulting formulation is not, however, adequate for most situations, as explained below.

Classification yards sort and group cars, dismantle and make-up trains. Yard workloads, costs and delays are usually mesured in terms of how many trains are received, dismantled and sorted, of the number of cars and groups of cars that are handled, of how many blocs and trains are formed for the other yards in the network. Yard delays are particularly sensitive to the traffic intensity and to the yard's specific characteristics and operating policies.

Petersen (1977a,b) presents a classical description of classification yard configurations, operations and performance mesures, as well as a series of models for the main yard operations. Several other authors have built upon these bases and Assad (1980a) and Crainic (1987), among others, present recent reviews of this subject. These models generally are network representations (more or less detailed, according to the planning level involved) of either the movements or the sequence of operations performed on the vehicles passing through the yard. Various queueing models are then used to derive the relevant yard performance mesures such as the average classification delay, the average number of cars classified in a time period or the mean total put-through time. This modeling is usually done at a lower level of detail than the one that we consider, generally requiring train or traffic routing information. Such detailed formulations are therefore not compatible with the aggregation level of a strategic model of regional/national multimode transportation systems. We resort then to an aggregate representation of classification yards that approximates the corresponding yard costs and delays using the product flow information exclusively.

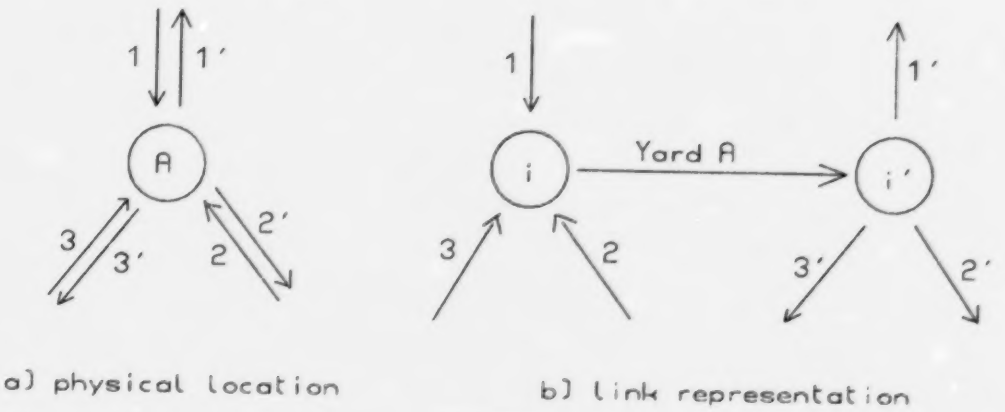


Figure 5. Yard representation

The particular cost and delay functions that relate to the yard model are presented in the following sections. Figure 5 illustrates the yard representation. A yard in the physical rail network is usually represented by a node of our network. This node is split, each one of the resulting nodes being the extremity of a link which now represents the classification yard. The origin node receives all the

incoming traffic, while the outgoing traffic exits via the destination node. The usual functions associated with links are then employed to approximate the yard throughput performance.

There is one situation where transfers, and their associated functions, could be used to model classification yards and operations. This is the case where only one rail line enters and exits the yard, which occurs when, for example, the yard is situated at the "entry" of a port and all trains have to pass through the yard to be dismantled and their cars be send to particular port terminals.

On this network, transportation activities are induced by the transportation demand. The demand is defined as a number of tons of a given product ($p \in P$), to be moved from an origin point (that is, a centroid in O) to a destination point (i.e., a centroid in D). Crainic, Florian and Guélat (1987a) describe in detail the tools available for demand modeling in STAN. Here, we will only emphasize the fact that the particularities of the rail mode require the explicit consideration of the demand for empty vehicles. We further examine this aspect of the demand in Section V.

4.2 Cost and flow modeling

The unit "costs" that are usually considered in aggregate models of the rail transportation system give, for yards, links and transfers, train and car operating costs in monetary units per train-km and car-km, respectively, train and car delay costs (covering crew costs, equipment and product depreciation, etc.) in monetary units par train-hour and car-hour, respectively, and train energy consumption factors that are dependent upon the link topography. Of course, the cost structure in a real rail system is significantly more complex, yet, for strategic (and even tactical) planning, these unit costs are sufficient to model most situations of interest.

The important fact to note in this context, is that practically all unit costs apply to vehicles and convoys. We have, therefore, to convert our flows of products (in tons) into corresponding numbers of cars and trains. Furthermore, this transformation has to be done locally, at the level of each individual link: car and train flows are not necessarily conserved at nodes. Several approximations have to be made.

We first assume that a *typical car* may be defined for each product $p \in P$ and that each product is exclusively transported by a typical car. This car may be defined, for example, by taking the weighted average (for each of their main characteristics) of the car types that most usually transport the product. This approximation may give mixed results for those commodities, e.g. general cargo, that are moved by several significantly different car types. Good results are obtained for commodities using either a limited number of car types or dedicated cars: minerals, petrochemical products, refrigerated foods, automobiles, etc. As this second product group usually forms the main rail traffic, this approximation is satisfactory. In particular, for each product $p \in P$, let w_p be the quantity of product p that may be loaded into the corresponding vehicle p and vw_p the weight of an empty vehicle p.

Consider a link a representing either a regular link, a connector, a transfer, or even a yard. Flows v_a^p of products $p \in P$ travel on this link. An equivalent number of rail cars, n_a^p for each product $p \in P$, is then:

$$n_a^p = v_a^p \,/\, w_p$$

To estimate t_a, the total train flow on link a, one may then simply use an average number of cars per train **n**:

$$t_a = \sum_{p \in P} n_a^p \,/\, n$$

which is an alternative quite often chosen in tactical rail models (e.g. Petersen and Fullerton, 1975, Assad, 1980b, etc.).

This "average" approach is a very rough approximation of the processes that lead to the determination of the different train services, of their various loads, of their frequencies and corresponding train lengths. First, the resulting train flows are real valued and, generally, grossly under-estimate the actual traffic. When, on the other hand, the computations are done in integer arithmetic (e.g., Assad, 1980b), the results largely over-estimate the actual traffic. Besides, this approach does not take into account any information on the type of products transported or on the physical path used to move the freight, and the aggregation effect is even stronger when computing in real arithmetic. Consequently, the train composition

and length usually are the result of trade-offs between economic and service criteria, product characteristics and physical constraints such as the maximum train length (imposed by the length of the sidings; in meters or number of cars) and the maximum train weight (due, mainly, to the infrastructure specifications). These trade-offs are normally included in tactical and operational models of rail operations.

In STAN, we searched for an approximation that is at the same time more aggregated than the tactical planning approaches and more precise than the simple "average" formula. The approximation is real valued and is computed locally, for each link, but it includes information on both product and link characteristics. The number of trains traveling on a particular link a is thus computed by the following formula:

$$t_a = \sum_{p \in P} \frac{v_a^p + (v_a^p / w_p) * vw_p}{\alpha_p * \beta_a}$$

where,

t_a : train flow on link a;

v_a^p : flow of product p on link a;

w_p : quantity of product p that may be loaded into the corresponding vehicle p;

vw_p : weight of an empty vehicle p;

α_p : weight of a train of product p;

β_a : link correcting factor.

This formula computes an *average train* for each product moving on the link and, then, combines them into the actual total link train flow, ajusting it for the characteristics of the particular link. The presence of both a product and a link transformation factor makes for increased flexibility and accuracy. In fact, our experiments, perfomed by using data from the Canadian National Railways (Crainic and Querin, 1987), clearly show that the "by product" approximation significantly outperforms the "average" approach, even when only the product adjusting factors (α_p) are calibrated and $\beta_a = 1$ for all links. We have also found that this

approximation gives an excelent fit in almost all cases. Slightly less accurate results are obtained only on links where small volumes of traffic are moved by a number of trains significantly larger than those normally corresponding to the intensity of the car and product flows. This, however, is an extreme condition, usually not present on the main lines, and that is easily taken care of by using the link correcting factor. See Crainic and Querin (1987) on the problem of the calibration of the individual α_p.

From a modeling point of view, it is interesting to note that different α coefficients may be used for one product by defining an adequate number of different commodities, all representing the same initial product, and by splitting the demand accordingly. This may be useful if one wants, for example, to discriminate among different origin-destination pairs. Practically however, this may rapidly and significantly increase the number of products, and thus the size of the problem, and caution should be exerted accordingly. As for the link correcting factor, it may be used to calibrate the train approximation formula to an "exact" fit for all links. This is an option that would, however, request an unacceptably long calibration effort in the case of most realistically sized networks. One would rather use the β_a factor to correct the estimation in extreme cases, as previously, or to "personalize" some parts of the network: lines of particularly low or high weight tolerance, subnetworks equipped with better traffic control and signalization equipment, etc.

The resulting estimation of the total link train flows are then used to account for the operating and energy consumption costs and to compute the line and yard delays generated by the traffic congestion and the limited facility capacities.

4.3 Delay estimation

Rail facilities, as those of other transportation modes, have physical capacities. There is an upper limit on the number of units (tons, cars, trains) that may pass through the facility during a specified time period. Well before the capacity of the facility is attained, however, this passing-through time, or *delay*, increases intolerably. This is caused by physical or operational bottlenecks and, when it occurs, it usually generates the redirection of the train traffic and, sometime, justifies the

study of some infrastructure modifications. These two related notions of performance, *facility capacity* and its associated *passing-through delay*, are among the main considerations at all levels of rail transportation modeling.

Delay functions are most important because they allow to analytically describe the effect of the traffic intensity on the facility by the time necessary to pass through the facility. Figure 6 illustrates the general shape of such a delay function: beginning with a *free running time*, it increases slowly, almost linearly (the *uncongested* or *linear* part) at first, until the facility starts to be congested and the delay strongly increases with the traffic intensity (the *congested* component) toward an asymptotic infinity at the facility's capacity. This is a typical delay function derived from queueing theory models.

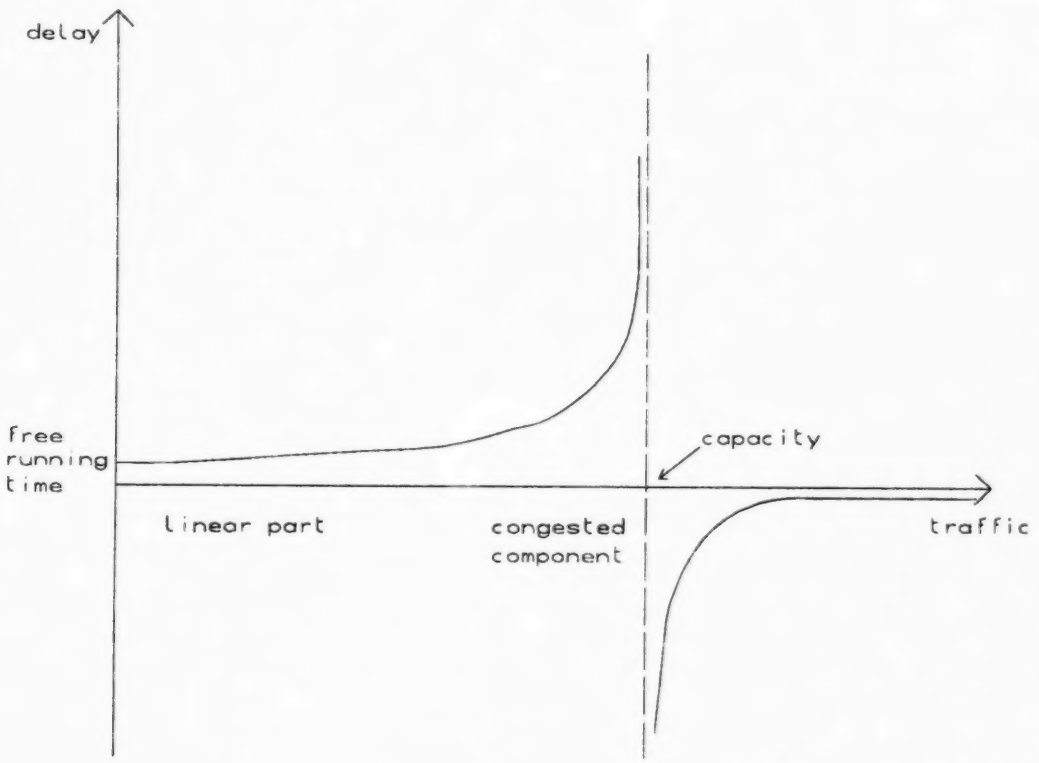


Figure 6. General shape of a delay function

Consequently, in models for tactic and strategic planning, capacities may not be explicitly considered and are replaced by delay functions, provided that

precautions are taken concerning their asymptotic behaviour. This is the approach of the present rail model and, in general, of STAN.

Delay functions are also important because they permit a better estimation of the total trip time, from the origin of the traffic to its destination. For instance, if modal choice is based on total trip time or, if specific *commodity delay costs* are defined accordingly, one may model different priority classes for the products and do the assignment following this criterion. And, with a reliable estimation of transportation time, vehicle depreciation costs may also be more easily computed.

Delay functions may be defined in yards, at transfers and over the lines of the network.

The various yard operations are usually grouped into five main categories: train reception, inspection and dismantlement, car classification and block formation, train make-up, waiting for train connection, train inspection and departure. Models are then fitted for each one of these main operations to estimate the yard's performance mesures. Various queueing models are usually used for this purpose (Crainic, 1987). For our model, we use a one-link representation of a classification yard and, therefore, we concentrate all these yard operations and delays into one function representing the *total yard put-through delay*. We then assume that the whole yard operation may be represented by an $M/M/1$ queue, whose mean waiting time represents the yard's average put-through delay. For a yard we then have:

$$Y_a = \frac{s_a * lp}{lp - s_a * \sum_{p \in P} (v_a^p / w_p)}$$

or, if one notes that, usually, $s_a = lp / CAP_a$,

$$Y_a = \frac{lp}{CAP_a - \sum_{p \in P} (v_a^p / w_p)}$$

where,

Y_a : Put-through yard delay for yard a;

v_a^p : Volume of traffic of product p transiting through yard a;

s_a : Average service (''classification'' or put-through) time for yard a;

CAP_a : Capacity of yard a;

lp : Length of the planning period.

This formula has two major drawbacks:

i) The asymptotic behavior (toward infinity) of the yard delay when the total car flow through the yard approaches the yard capacity;

ii) The convexity of the objective function for the general model cannot be formally demonstrated when it includes this type of delay formula.

Empirically, the average service time and capacity may be quite difficult to evaluate precisely in most cases. For yards there is not, as there is for rail lines (e.g., Colson's formula), an accepted method that may be used to compute, under simplifying assumptions , a reasonably accurate estimate of their capacities; often, only historically observed yard put-through values are available.

Consequently, when the yard is not a bottleneck in a given network, nor is it forecast to became one in a future scenario, a constant (estimated from observed values) delay function may be used for Y_a. The capacity may then be introduced in that function as a limiting factor, by, for example, penalty methods (Guélat, 1987). Otherwise, the yard put-through delay defined above should be taken as a starting point and a polynomial delay $\overline{Y}_a$ should be approximated using the procedure described below.

On the lines of a rail network, train meetings and overtakes can occur only at prespecified points in the network: stations or sidings. Delays are thus incured, and they increase with the traffic intensity and complexity.

A number of hypotheses on the nature of the train traffic were assumed for our model:

a) Passenger trains are not present on the network;

b) All freight trains have equal priority;

c) On a link, all trains moving in the same direction, travel at the same (and constant) speed;

d) Consequently, no more than two trains meet at the same time;

e) On each link, the traffic is globally balanced, meaning that the number of trains traveling in each direction is approximately the same.

These hypotheses were inspired by the context of the brazilian transportation system and by the needs of strategic planning and are appropriate for a large variety of applications. Given these hypotheses, no train overtakes may occur on the line of the network and the over-the-line delay for a train traveling on a double track line is equal to the *free running time* of the corresponding link. In this case, the line capacity may also be included in the delay function by using penalty methods (Guélat, 1987).

The average over-the-line delay for a train traveling on a single track link may be computed by different formulae according to the degree of detail that is sought after (Crainic, 1987). Given the strategic context of the model and our hypotheses, we employ a formula, first proposed by Petersen (1974), that makes use of the capacity of the line and the train flows in each direction:

$$D_a = \frac{FRT_a * CAP_a + (FRT_{\bar{a}} * t_{\bar{a}} - FRT_a * t_a)}{CAP_a - (t_{\bar{a}} + t_a)}$$

where the two links a and $\bar{a}$ represent the two directions of travel on a single track rail line and where,

D_a : delay on link a;

CAP_a : capacity of link a;

FRT_a : free running time on link a;

$FRT_{\bar{a}}$: free running time on link $\bar{a}$;

t_a: train flow on link a;

$t_{\bar{a}}$: train flow on link $\bar{a}$.

We identified several problems related to the above formula. The first two

i) Asymptotic (toward infinity) behavior of the delay when the total train flow tends toward the link capacity (see Figure 6);

ii) The convexity of a general objective function that includes this delay formula cannot be formally demonstrated;

are common to this class of delay functions and were also identified for the yard delay formula. There is another one that is even more disturbing in the present context:

iii) When fully developed, by substituting the equation for the number of trains, the formula consists of too many terms, implying a more difficult user interface and much more time consuming algorithms, particularly the shortest path procedure.

We propose therefore a polynomial approximation of the delay function:

$$\overline{D}_a = FRT_a * (1 + \phi_1 * T_a + \phi_2 * (T_a / CAP'_a)^{exp})$$

where,

$\overline{D}_a$: estimate (approximation) of delay on link a;

T_a : total train flow on the link

$$T_a = t_a + t_{\bar{a}}$$

CAP'_a : value of the total train flow where the line begins to be considered congested;

and ϕ_1, ϕ_2, and exp are parameters to be calibrated.

The parameters could be calibrated by non-linear regression methods and Crainic and Querin (1987) examine this option. This approach is not, however, entirely satisfactory for real applications, since too large a number of different polynomials would be generated (in fact, a different polynomial for each link of the network!). Also, the degree of the polynomials generated by non-linear regression methods are, generally, quite high, resulting in possible numerical problems and longer solution times for the algorithm.

A heuristic procedure may rather be used to calibrate the parameters of the polynomial approximation. The procedure estimates values for the three parameters, exp, ϕ_1 and ϕ_2, of the polynomial delay $\overline{D}_a$, such that it fits closely to the

delay D_a computed by a given formula (e.g. Peterson's link delay (1974), yard classification delay, or other similar function).

For link a, the general procedure is:

1) Generate a set of points (T_a, D_a) = (total train traffic, delay), where $T_a = t_a + t_{\bar{a}}$, for various combinations of train flows t_a et $t_{\bar{a}}$. Fix the value of CAP'_a at the level of the total train flow where the link "begins" to be considered congested.

2) Plot the points obtained in step 1, "observe" the curvature of the scatter diagram and fix exp accordingly.

3) Estimate ϕ_2 by fitting

$$D_a = FRT_a * (1 + \phi_2 * (T_a / CAP'_a)^{exp})$$

for high values of T_a, i.e. $T_a \geq CAP'_a$.

4) Evaluate ϕ_1 to adjust

$$D_a = FRT_a * (1 + \phi_1 * T_a^* + \phi_2 * (T_a^* / CAP'_a)^{exp})$$

for a point in the linear part of the scatter diagram, e.g. $T_a^* \in [0{,}1 * CAP_a, 0{,}2 * CAP_a]$, and the value of ϕ_2 calculated at step 3.

5) Repeat steps 2 to 4 for "intelligent" choices of exp and choose the best fit polynomial.

Crainic and Querin (1987) have tested this procedure and report excelent results, even when compared to estimating the parameters directly with nonlinear regression methods. They also present some practical suggestions on how best to use the procedure, especially for the links of a realistically large network.

V. EMPTY FLOW ESTIMATION

An important aspect of any freight transportation system is the presence of a significant, both in terms of volume and costs, traffic of empty vehicles. This traffic is usually generated by the imbalances in the transportation demand, the fact that specialized vehicles are used for certain products and the need to relocate the vehicles in view of the transportation requirements of the following periods.

The impact of empty vehicle movements on both the operations and planning of transportation systems, which is significant for all transportation modes, is even more important for the rail mode, since rail vehicles are captive to the infrastructure and thus, the empty car movements occur on the same rail lines as the loaded ones. Often, empty and loaded cars are mixed together to form blocks and trains. Consequently, the train flows and the over-the-line delays are significantly increased and, therefore, the proper modeling of strategic or tactical rail planning has to include some form of representation of empty car movements.

Since a strategic model of the freight rail transportation system, such as STAN, considers only product flows and estimates the train congestion at the link level, one must include a mechanism to allocate to each link a certain amount of empty car movements to be considered, while computing the train flow and the corresponding over-the-line delay.

The conditions that we impose on such a mechanism specify that it should use only the information currently available in the model (i.e., the loaded transportation demand and current traffic pattern) and that the resulting empty car allocation should change with the variations in the routing of the loaded traffic during the solution of the multimodal multicommodity assignment problem.

A relatively important number of models have already been proposed for the empty vehicle transportation problem, for all modes and at various planning levels. Dejax and Crainic (1987) present a thorough review and analysis of these models. For our part, we decided to use a procedure based on a gravity model similar to the the one successfully used by Coutu (1978) for the forecasting of the empty rail car traffic for the Canadian National Railways. We first present the general approach

and the details of the gravity model, followed by the statement of the calibration procedures for the parameters of the model. We conclude with the presentation of two possible utilization modes for the empty flow estimation procedure in strategic analyses to be performed by STAN in practice.

5.1 The procedure

The link flows in our model are the result of the assignment procedure in STAN. Consequently, the most effective and convenient approach to treat the empty car flow estimation problem in concordance with the general principles of STAN is to define the empty cars as a separate *product*.

The product *empty car* will then be transported, to satisfy a certain origin-destination demand, concurently with the other products, thus contributing to the general network congestion, delays and costs. The general procedure is:

1) Define the *empty car* product and its transportation characteristics;
2) Estimate the origin-destination demand matrix for this product;
3) Include this demand in the general model and treat it as any other product.

To define a product, one has to name it and to specify, for each mode, the characteristics of the vehicle that is used to transport it, as described in Section 4.2. Theoretically, one could define an *empty car* commodity for each one of the products and vehicles present in a particular application. This would generate, however, a large number of additional products that would very rapidly became prohibitive in terms of memory and computing time requirements. It should be noted that we are not interested in the exact reproduction of the actual car traffic in the network and, also, that the vehicles associated with products in STAN are already "average" or "typical" vehicles, one per product. Consequently, *one* product should be enough for the estimation of the link empty car flow and the rest of this section is based on this hypothesis. If it became necessary to consider several *empty car* products, the same procedure applies for each one of these.

Our *empty car* product is identified by the ω character. Its associated vehicle for the rail mode (the product ω is not transported on any mode that is not rail based) is a combination of the "loaded" vehicles already defined for the transportation, by

the rail modes, of the products of a specific application. Its loading factor, w_ω, equals the weighted average of the w_p values that correspond to the loading factors of these vehicles. As for its empty weight, vw_ω, it is fixed at zero to avoid a double counting in the train estimation formula. The various unit costs usually associated with products and their *typical* vehicles, may be, for the *empty car* product, either exogenously defined, or derived, by using weighted averages, from the corresponding attributes of the "loaded" vehicles.

To estimate the origin-destination demand of empty movements, one could use a variety of heuristic and exact methods (Dejax and Crainic, 1987). We adopt the use of a *gravity* model (Coutu, 1978; Nguyen, 1984) that assumes that the empty flow between a given origin-destination pair is proportional to the supply at the origin and the demand at the destination; the proportionality factor usually depends on parameters such as distance and the cost of travel between the two centroids. The formulation also assumes that the allocation of empty car movements among the different origin-destination pairs is stable from one planning period to another. The model is:

$$\textit{Determine} \qquad g_{od}^{\tau} = \gamma_o * \theta_d * r_k \qquad \forall o \in O, \forall d \in D$$

$$\textit{Subject to} \quad \sum_{o \in O} g_{od}^{\tau} = D_d^{\tau} \qquad \forall d \in D$$

$$\sum_{d \in D} g_{od}^{\tau} = S_o^{\tau} \qquad \forall o \in O$$

$$g_{od}^{\tau} \geq 0 \qquad \forall o \in O, \forall d \in D$$

where,

- g_{od}^{τ} : The origin-destination demand to be determined, i.e. the number of empty cars to be moved from origin $o \in O$ to destination $d \in D$ in period τ;
- γ_o, θ_d : Balancing coefficients;
- r_k : Balancing coefficient for distance (cost) class k;
- S_o^{τ} : Supply of empty cars at origin $o \in O$, in period τ;
- D_d^{τ} : Demand of empty cars at destination $d \in D$, in period τ.

The model determines the demand for each origin-destination pair such that the total supply is shipped out of surplus centroids while each deficit centroid receives its total demand. The allocation is done according to the class k to which belongs the origin-destination pair following prespecified criteria (cost, distance, flows, etc.). Thus, the corresponding r_k factors represent weights that indicate, with respect to a *base year*, the relative importance of each class and, therefore, of the empty flow to be allocated to each origin-destination pair in that class. The allocation may also be ajusted for known, or forecasted, variations of supplies and demands at centroids through the *balancing* coefficients γ_o and θ_d. These are obtained from a balancing procedure with predicted S_o^τ and D_d^τ.

We discuss in the following sections the calibration of the distance balancing coefficients and the estimation of the supplies and demands at centroids for the planning period under consideration. Assuming that these quantities are known, however, the *prediction model* may be solved by a two-dimensional balancing procedure (see Nguyen (1984) for details on this type of procedure):

STEP 0. For all origin-destination pairs (o,d), $o \in O$, $d \in D$, let $g_{od}^\tau = r_k$ if (o,d) belongs to distance class k, 0 otherwise;

STEP 1. For all $o \in O$, let $g_{od}^\tau = \dfrac{g_{od}^\tau * S_o^\tau}{\sum\limits_{d \in D} g_{od}^\tau}$

STEP 2. For all $d \in D$, let $g_{od}^\tau = \dfrac{g_{od}^\tau * D_d^\tau}{\sum\limits_{o \in O} g_{od}^\tau}$

STEP 3. If $\left[\dfrac{S_o^\tau}{\sum\limits_{d \in D} g_{od}^\tau} \approx 1 \right]$ and $\left[\dfrac{D_d^\tau}{\sum\limits_{o \in O} g_{od}^\tau} \approx 1 \right]$

STOP, else go to STEP 1.

The result of this procedure is the empty car demand matrix g_{od}^τ for the planning period τ, and the balancing coefficients.

5.2 Supply and demand estimation

The supplies and demands of empty cars at the centroids of the network are estimated as the difference between the number of arriving and departing loaded cars at each centroid. According to the existing information, there are two slightly different computation methods based on this principle:

CASE 1. Product volumes are known, possibly following a previous assignment, on the links of the network. Then, if A_j^+ represents the set of connectors going out of centroid j, while A_j^- stands for the set of connectors going into centroid j, the supplies at origins o, $o \in O$, are computed as

$$S_o^\tau = \max \{ 0, \sum_{A_o^-} \sum_{p \in P} (v_a^p / w_p) - \sum_{A_o^+} \sum_{p \in P} (v_a^p / w_p) \}$$

while the demands at destinations d, $d \in D$, are equal to

$$D_d^\tau = \max \{ 0, \sum_{A_d^+} \sum_{p \in P} (v_a^p / w_p) - \sum_{A_o^-} \sum_{p \in P} (v_a^p / w_p) \}$$

CASE 2. No information is available on product flows, only the total product supplies and demands at centroids are known. Then, the empty car supplies and demands are computed by the following formulae:

$$S_o^\tau = \max \{ 0, \sum_{p \in P} \sum_{d \in D} g_{od}^p / w_p - \sum_{p \in P} \sum_{o \in O} g_{od}^p / w_p \}$$

$$D_d^\tau = \max \{ 0, \sum_{p \in P} \sum_{o \in O} g_{od}^p / w_p - \sum_{p \in P} \sum_{d \in D} g_{od}^p / w_p \}$$

5.3 Model calibration

Various *costs*, or *impedances*, may be used to determine the r_k coefficients for the allocation of the empty flows to the different origin-destination pairs: travel times, transportation costs, previous flows, etc. Following the method of Evans and Kirby (1974), the domain of the measure of impedance is divided in several intervals, or classes, and if the impedance of an origin-destination pair falls in interval k then the pair belongs to class k and its cost is the coefficient r_k. The lengths of the intervals are application specific but should not be too small to attenuate the impact of variations between the *base year* and the planning period under study.

Best results were obtained by Coutu (1978) when the mesure of impedance was the inverse of the observed empty flows between the origin-destination pairs. Then, between an origin-destination pair (o,d), $o \in O$, $d \in D$, a flow g_{od}^b of empty cars was observed in the *base year* **b**, and the pair is said to belong to class C_k if

$$\frac{1}{g_{od}^{k-1}} < \frac{1}{g_{od}^b} \leq \frac{1}{g_{od}^k}.$$

The calibration of the r_k cost coefficients is performed by assuming that the distribution of the empty car demand in the *base year* verifies the following model:

$$\textit{Determine} \quad g_{od}^b = \overline{\gamma}_o * \overline{\theta}_d * r_k * \delta_{od}^k \qquad \forall o \in O, \forall d \in D, \forall k$$

$$\textit{Subject to} \quad \sum_{o \in O} g_{od}^b = D_d^b \qquad \forall d \in D$$

$$\sum_{d \in D} g_{od}^b = S_o^b \qquad \forall o \in O$$

$$\sum_{C_k} g_{od}^b = R_k^b \qquad \forall k$$

$$g_{od}^\tau \geq 0 \qquad \forall o \in O, \forall d \in D$$

where,

δ_{od}^k : 1 if $(o,d) \in C_k$ and 0 otherwise;

R_k^b : Total empty car traffic observed for class k;

$$R_k^b = \sum_{C_k} g_{od}^b \qquad \forall\, k$$

S_o^b : Total observed empty car traffic out of origin o

$$S_o^b = \sum_{d \in D} g_{od}^b \qquad \forall o \in O$$

D_d^b : Total observed empty car traffic in destination d;

$$D_d^b = \sum_{o \in O} g_{od}^b \qquad \forall d \in D$$

A three-dimentional balancing procedure is then used to determine the r_k coefficients and thus calibrate the gravity model. Note that the estimation of g^b_{od} is a by-product of the calibration procedure that is not needed afterwards. The procedure:

STEP 0. Let $r_k = 1$ for all classes k;

For all origin-destination pairs (o,d), $o \in O$, $d \in D$, let $g^b_{od} = \delta^k_{od} * r_k$

STEP 1. For all $o \in O$, let $g^b_{od} = \dfrac{g^b_{od} * S^b_o}{\sum_{d \in D} g^b_{od}}$

STEP 2. For all $d \in D$, let $g^b_{od} = \dfrac{g^b_{od} * D^b_d}{\sum_{o \in O} g^b_{od}}$

STEP 3. For all classes k, let $r_k = \dfrac{r_k * R^b_k}{\sum_{C_k} g^b_{od}}$ and $g^b_{od} = \dfrac{g^b_{od} * R^b_k}{\sum_{C_k} g^b_{od}}$

STEP 4. If $\left[\dfrac{S^b_o}{\sum_{d \in D} g^b_{od}} \approx 1\right]$ and $\left[\dfrac{D^b_d}{\sum_{o \in O} g^b_{od}} \approx 1\right]$ and $\left[\dfrac{R^b_k}{\sum_{C_k} g^b_{od}} \approx 1\right]$

STOP, else go to STEP 1.

The resulting r_k coefficients may then be used, with the estimations of the total supplies and demands, to forecast the origin-destination demands for empty car travel.

5.4 Utilization modes

STAN is usually used to analyse future, forecasted or hypothetical, situations and to compare the results of these scenarios to some given base year data. It is thus of interest to examine how to use the empty flow estimation procedure in these cases.

One should first note that data from a *base year* is always required to calibrate the r_k cost coefficients and that following that operation the *balancing* coefficients

may be used to ajust the relative weights of the centroids to the forecasted environment. Secondly, it should also be noted that one may use STAN in either of two modes: to perform a *multiperiod* analysis or a *one period* study.

For a *multiperiod* analysis, an assignment is performed for each period and the demand matrices, and eventually the network, are ajusted before each new period. Then, the CASE 1 of Section 5.2 applies and the supplies and demands of empty cars for a new period are estimated from the product flows determined at the previous period. Additionally, the empty car demand matrix of the previous period is used as the *base year* data. When, on the other hand, one performs a *one period* study, this information is not available and the estimation has to be done as described in the second case of Section 5.2. It is obvious that, in this situation, the overall empty flow estimation would not be very accurate: the r_k cost coefficients are calibrated using data that may be quite different from that of the current scenario, and the total empty car supply and demand for the period are estimated using the transportation demand for loaded movements for the same period. However, this is a far better solution than that adopted by most strategic planning models that choose to ignore the empty flow problem altogether.

We want finally to emphasize that, when information is available on certain empty car movements, such as the knowledge that the cars moving a certain product between a given origin-destination pair are always going back empty to the origin, this information should be included in the empty flow estimation model by fixing the corresponding demand. That would result in a more accurate prediction and better overall results.

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